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Deflection and tearing of clamped stiffened circular plates subjected to uniform impulsive blast loads

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ABSTRACT

The large deformation of structural components such as beams, plates and shells subjected to blast loads can be predicted with favourable correlation with experimental data. This work deals with the more complex situation of combining these structural components. Experiments using a 100mm diameter circular plate stiffened with a single beam of width 8mm clamped across the diameter of the plate is presented. Beams of thickness 3,4,5 and 6mm were used. Results show that an optimum beam-thickness/plate-thickness combination is required.

1. INTRODUCTION

The prediction, as a result of a blast load, of the large deformation of structural components with symmetrical cross-sections such as beams, plates and shells, has been reported widely in the literature, for example Jones [1,2,3], Nurick and Martin [4,5], Duffey [6]. In addition, the prediction of the deformation and subsequent tearing has also been reported, for example Shen and Jones [7,8], Teeling-Smith and Nurick [9], Olson, Nurick and Fagnan [10], Nurick and Shave [11]. However, some structures that may be subjected to blast-type loads are constructed in combinations of components and therefore have assymmetrical cross-sections. Nurick, Olson, Fagnan and Levin [12] reported on the deformation and tearing of stiffened square plates, where the stiffener and the plate were manufactured as a single unit, while Nurick and Conolly [13], reported on clamped single and double stiffened rectangular plates. Both the asymmetry and boundary fixing conditions create added complications in the modelling process. The implications of assymmetrical cross-sections have been investigated for T-beams by considering the interactive yield curves as reported by Nurick and Jones [14,15.] The respective responses of the individual components are crucial in the overall design process. For example, if the beam response dominates then the plate will tear and where the inverse is true, then the beam will fail first. This phenomenon is illustrated in this paper, in which the results of a series of experiments are presented.

2. EXPERIMENTAL PROCEDURE

Three series of experiments were performed consisting of a series on plates alone, a series on beams alone and a series on the combined plate and beam for each beam thickness. The mild steel plates and beams were clamped between two heavy securing plates using 10mm bolts equally spaced. The photographs in Fig 1. show the clamping arrangement for the beam-plate configuration. The plate test diameter was 100mm with a plate thickness of 1.6mm. All the beams were 8mm wide and were also clamped using a 100mm span. Four different beam thicknesses were used; 3, 4, 5 and 6mm. In all cases the clamped specimens were attached to one end of a ballistic pendulum which was counter-balanced as described in Ref [9]. For all experiments an uniform load was applied using plastic explosive. For the plates the explosive was applied as two annuli rings interconnected as described in Ref [9]; and for the beams the explosive consisted of a single strip along the full span of the beam. In the case of the combined structure the explosive was applied to the plate as two-interconnected annuli rings. In all cases the detonator was attached at the centre of the explosive to enable symmetric loading. The total applied impulse was determined from the displacement of the pendulum. The deformation of the specimens was measured after detonation. Tables 1,2 and 3 give the results for plates, beams and combined components, respectively.

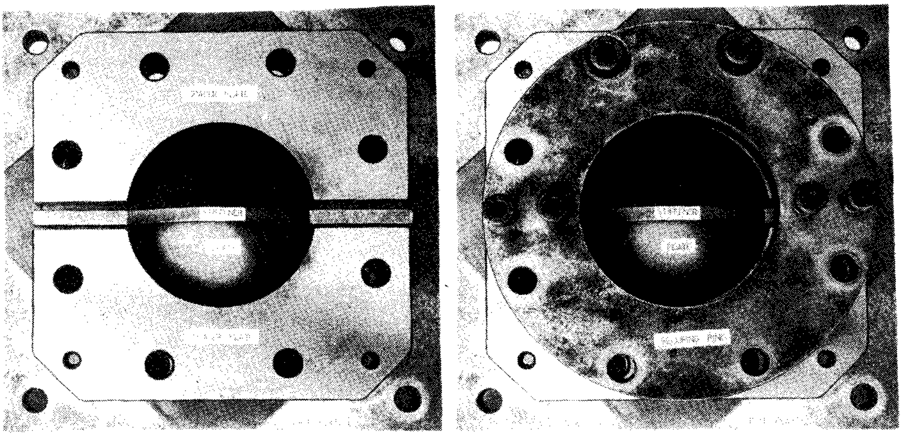

FIG.1. Photographs showing the Clamping Arrangement

Test No.	Impulse (Ns)	Mid-Point Deflection (mm)	Deflection-Thickness Ratio
0890P1	8.73	10.65	6.66
0890P2	5.21	7.26	4.54
0890P3	14.68	19.09	11.93
0890P4	7.41	9.97	6.23
0890P5	16.47	20.43	12.77
0890P6	10.08	13.81	8.63
0890P7	16.25	(1)	-
0890P8	14.48	19.89	12.43

Table 1. Data for Plate Experiments

(D) 3mm Thick Beams

Test No.	Impulse (Ns)	Mid-Point Deflection (mm)	Deflection-Thickness Ratio
0890B35	1.06	7.70	2.57
0990B79	1.23	9.02	3.01
0990B80	1.64	12.28	4.09
0990B81	2.38	15.22	5.07
0990B82	2.77	(1)	-
0990B83	2.59	16.66	5.55
0990B84	2.71	(1)	-
0990B85	2.81	17.52	5.84

(C) 4mm Thick Beams

Test No.	Impulse (Ns)	Mid-Point Deflection (mm)	Deflection-Thickness Ratio
0990B69	1.65	9.14	2.29
0990B70	2.48	13.02	3.26
0990B71	2.81	14.78	3.69
0990B72	3.26	15.34	3.84
0990B73	3.77	19.68	4.92
0990B74	1.34	6.98	1.75

(B) 5mm Thick Beams

Test No.	Impulse (Ns)	Mid-Point Deflection (mm)	Deflection-Thickness Ratio
0890B42	0.89	2.38	0.48
0890B43	1.19	3.46	0.69
0890B44	1.61	6.38	1.28
0890B45	2.52	10.88	2.18
0890B46	2.77	12.44	2.49
0890B47	3.33	14.70	2.94
0890B48	2.08	8.26	1.65
0990B96	4.31	(1)	-
0990B97	3.72	15.74	3.15
0990B98	4.13	19.76	3.95

(A) 6mm Thick Beams

Test No.	Impulse (Ns)	Mid-Point Deflection (mm)	Deflection-Thickness Ratio
0990B57	3.24	9.24	1.54
0990B58	4.14	13.76	2.29
0990B59	4.43	14.08	2.35
0990B60	2.75	9.14	1.52
0990B61	2.05	5.62	0.94
0990B92	3.24	10.76	1.79

Table 2. Data for Beam Experiments

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(D) 3mm Beam				
Test No.	Impulse (Ns)	Mid-Point Deflection (mm)		
		Plate	Beam	Gap
0890PB27	6.54	6.70	8.50	1.80
0890PB28	13.71	13.08	14.68	1.60
0890PB29	8.50	10.24	10.86	0.62
0890PB30	13.30	13.22	14.94	1.72
0890PB31	7.61	7.52	8.78	1.26
0890PB32	18.23	19.59	(2)	
0990PB75	7.64	6.42	8.36	1.94
0990PB76	7.70	6.62	8.82	2.20
0990PB77	24.21	(1)	-	
0990PB78	5.21	4.64	5.74	1.10
0990PB86	5.25	5.50	5.98	0.48
0990PB93	20.24	20.02	21.53	1.51
0990PB94	8.35	7.56	8.97	1.41
0990PB95	19.01	19.42	20.73	1.31

(A) 6mm Beam				
Test No.	Impulse (Ns)	Mid-Point Deflection (mm)		
		Plate	Beam	Gap
0890PB1	10.86	9.48	10.64	1.16
0890PB2	16.34	15.36	17.64	2.28
0890PB4	18.53	(1)	-	-
0890PB5	18.90	(1)	-	-
0890PB6	18.26	(1)	-	-
0890PB7	19.25	(1)	-	-
0890PB8	12.19	11.78	12.84	1.06
0890PB9	15.92	(1)	-	-
0890PB10	19.49	(1)	-	-
0890PB11	11.36	11.82	12.64	0.82
0890PB12	6.80	4.68	5.88	1.20
0890PB13	15.17	12.63	13.12	0.49
0890PB14	14.90	13.53	14.62	1.09
0890PB15	14.19	14.69	15.54	0.85
0990PB87	15.74	11.98	13.10	1.12
0990PB88	7.38	5.74	6.97	1.23
0990PB89	8.58	6.62	7.63	1.01

(C) 4mm Beam				
Test No.	Impulse (Ns)	Mid-Point Deflection (mm)		
		Plate	Beam	Gap
0890PB16	8.87	8.12	9.80	1.68
0890PB17	15.69	1.92	15.24	1.32
0890PB18	18.26	16.81	(2)	
0890PB19	13.50	15.45	16.48	1.03
0890PB20	7.70	6.58	8.62	2.04
0890PB21	19.61	18.24	(2)	
0890PB25	14.88	12.82	14.30	1.48
0990PB49	7.90	8.04	9.76	1.72
0990PB50	6.68	6.62	8.70	2.08
0990PB51	19.24	(1)	-	
0990PB52	17.93	16.36	18.72	2.36
0990PB53	21.45	(1)	-	
0990PB54	19.77	(1)	-	
0990PB55	7.75	6.82	8.86	2.04
0990PB56	18.89	16.40	17.52	1.12
0990PB63	13.19	13.52	14.68	1.16
0990PB66	7.07	5.98	7.82	1.84
0990PB67	3.09	3.54	4.44	0.90
0990PB68	5.39	5.38	7.16	1.78

(B) 5mm Beam				
Test No.	Impulse (Ns)	Mid-Point Deflection (mm)		
		Plate	Beam	Gap
0890PB36	11.90	9.99	11.02	1.03
0890PB37	14.91	12.90	14.30	1.40
0890PB38	12.77	13.78	15.02	1.24
0890PB39	16.21	15.12	16.06	0.94
0890PB40	16.43	15.14	16.14	1.00
0890PB41	9.10	7.26	8.70	1.44
0990PB64	19.49	(1)	-	-
0990PB65	19.43	16.44	18.22	1.78
0990PB90	8.09	6.34	7.48	1.14
0990PB91	6.78	5.18	6.18	1.00
0990PB92	7.19	5.96	7.18	1.22

Table 3. Data for Plate-Beam Experiments

Uniaxial tensile tests were performed on standard specimens at different quasi-static strain rates. The average static yield stress was determined using the Cowper-Symonds strain rate equation with the accepted strain rate sensitivity values for mild steel [16].The average static yield stress for the plate material was 255 MPa and for the beam material was 427 MPa.

3. RESULTS

The mid-point deflection versus impulse for the beams is shown in Figs.2a and 2b. It is clearly observed that the thicker beams deform less than the thinner beams for similar impulses. All this data presented in the form deflection-thickness ratio versus dimensionless impulse generally falls within the predictions [16] using circumscribing and inscribing yield criteria with strain rate sensitive material properties, as shown in Fig.3. A similar trend is also found for the results of the plate data as shown in Fig.4, (although in this case the experimental results are all slightly less than the circumscribing yield curve. It has been reported [16] that for large deflections the experiments will lie closer to the lower bound). However, the information in Figs. 3 and 4 provide a sense of confidence in the experimental process in order that the stiffened plate experiments could proceed. The mid-point deflection for the stiffened plate versus impulse is shown for each plate-beam combination in Figs 5-8.

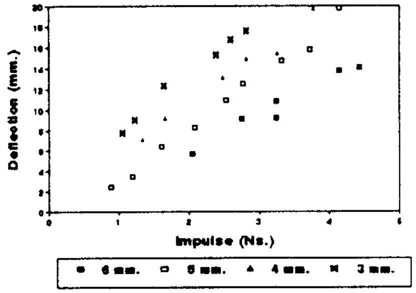

FIG 2a. Graph of Deflection Versus Impulse for Beam Tests.

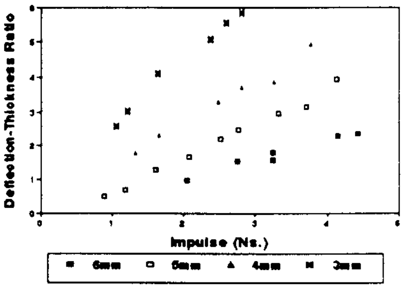

FIG 2b. Graph of Deflection- Thickness Ratio Versus Impulse for Beam Tests.

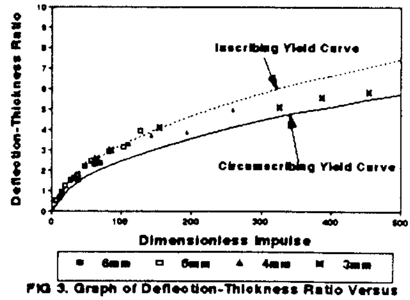

FIG 3. Graph of Deflection-Thickness Ratio Versus Dimensionless Impulse for Beams.

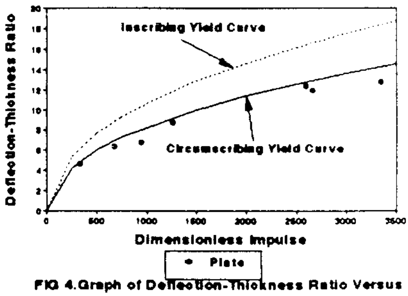

FIG 4.Graph of Deflection-Thickness Ratio Versus Dimensionless Impulse for Plates.

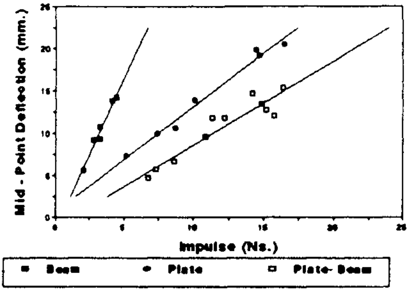

Fig 5. Graph of Deflection Versus Impulse for 6mm Beam Stiffened Plate.

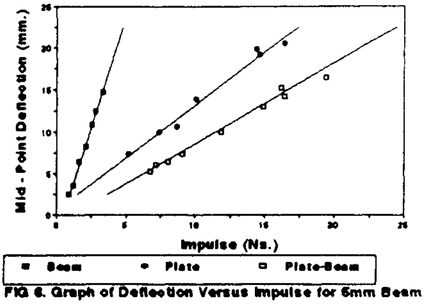

FIG 6. Graph of Deflection Versus Impulse for 5mm Beam Stiffened Plate.

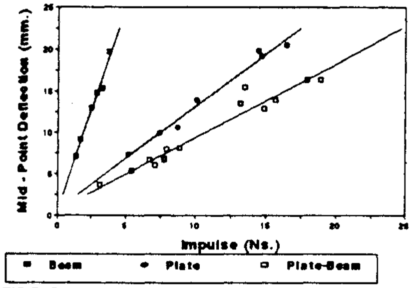

FIG 7. Graph of Deflection Versus Impulse for 4mm Beam Stiffened Plate.

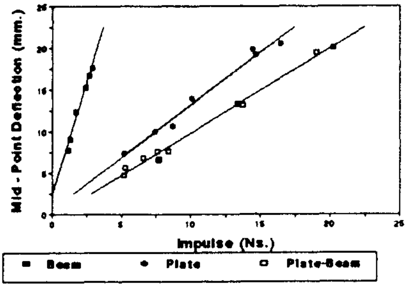

FIG 8.Graph of Deflection Versus Impulse for 3mm Beam Stiffened Plate.

It is apparent that the beam contributes to an overall reduction in the deflection of the plate, although the contribution as a function of the beam thickness is difficult to assess from Figs. 5-8. In order to evaluate the effect of the different thickness beams on the deflection of the plate, information is obtained using the general trends given by the best fit linear regressions. In general the mid-point deflection decreases asymptotically as the beam stiffener thickness increases for similar values of impulse, as shown in Table 4 and Fig.9. Also the mid-point deflection percentage decrease (relative to plate only deflection) increases as the beam thickness increases, as illustrated in Fig.10.

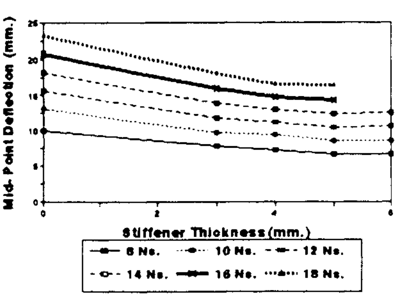

FIG 9. Graph Showing Effect of Beam Thickness on Plate.

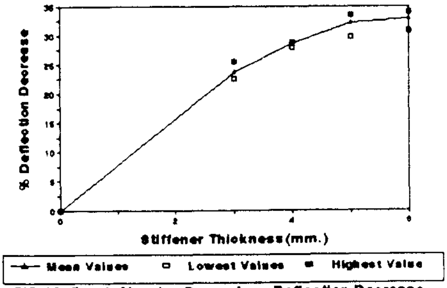

FIG 10. Graph Showing Percentage Deflection Decrease for Increasing Stiffener Thickness.

Impulse (Ns)	Deflection (mm)				
	Plate	Stiffened Plate			
		3mm	4mm	5mm	6mm
8	10.06	7.79 (22.6)	7.24 (28.0)	6.70 (33.4)	6.64 (34.0)
10	13.18	9.82 (25.5)	9.42 (28.5)	8.62 (34.6)	8.63 (34.5)
12	15.69	11.85 (24.8)	11.20 (28.6)	10.54 (32.8)	10.62 (32.3)
14	18.20	13.88 (23.7)	12.98 (28.7)	12.46 (31.5)	12.61 (30.8)
16	20.71	15.92 (23.1)	14.75 (28.8)	14.39 (30.5)	-
18	23.23	17.95 (22.7)	16.53 (28.8)	16.31 (29.8)	-

Table 4. Comparisons of Figs. 5-8 (Values in brackets are percentage decrease relative to plate only).

Structure	Range (mm)	Average (mm)
PB 6	0.49 - 2.28	1.12
PB 5	0.94 - 1.78	1.22
PB 4	0.90 - 2.36	1.61
PB 3	0.48 - 2.20	1.41
Average		1.36

Table 5. Gap Between Plate and Beam

It was observed that in all cases, the permanent mid-point deflection of the beam was greater than the mid-point deflection of the plate as shown in the photograph in Fig.11. A similar phenomenon was observed in Ref[13]. This is attributed to the springback effect referred to in Ref[10]. No dependency on beam thickness could be identified for the variation of the gap size between the beam and the plate. In all cases the gap varied within the range 0,48mm to 2,36mm.

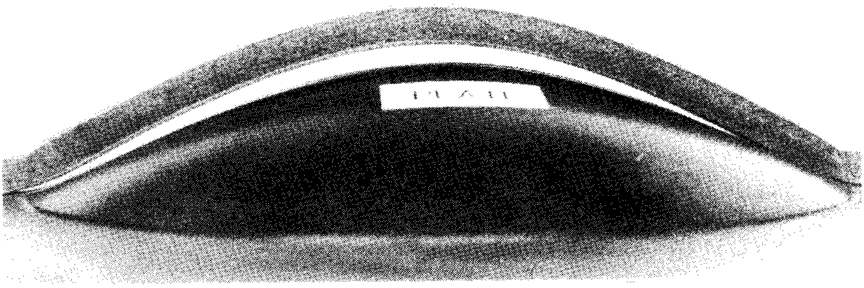

Fig.11. Photograph showing the Gap Between the Plate and the Beam.

The tearing of the plate or the beam at the boundary was observed to occur in a small range of impulses. These values were similar to the highest impulse for no tearing, as shown in Table 6 and Fig.12. In Table 6 Mode I refers to deformation without tearing and Mode II refers to deformation with tearing. For the 3mm and 4mm thick beams, the beam tore at impulses lower than that required for plate tearing, while the inverse is true for the 5mm and 6mm thick beams. The photograph in Fig.13 illustrates the tearing of a plate which was stiffened by the thicker beams.

Beam Depth (mm)	Mode (I,II)	Impulse (Ns)	Mid-point deflection	
			Plate	Beam
6	I	16.34	15.36	17.64
	II	15.92	(1)	-
5	I	19.43	16.44	18.22
	II	19.49	(1)	-
4	I	18.89	16.40	17.52
	II	19.24	(1)	-
	I,II	18.26	16.81	(2)
3	I	20.24	20.02	21.53
	II	24.21	(1)	-
	I,II	18.23	19.59	(2)
0	I	16.47	20.43	-
	II	16.25	(1)	-

(1) Plate tore at boundary
(2) Beam tore at boundary

Table 6. Values of Impulse at Tearing

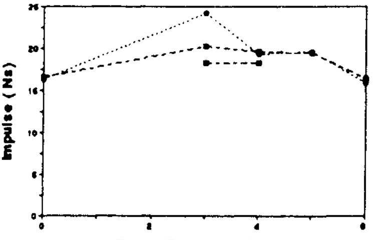

FIG 12. Graph Showing Impulse for Plate and Beam Tearing.

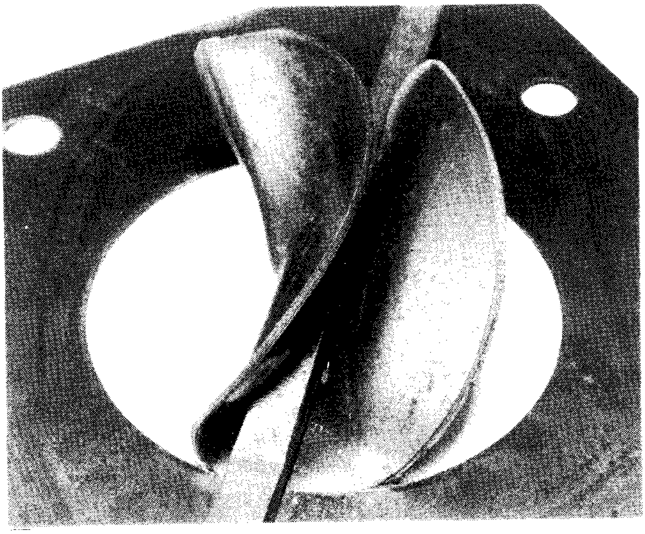

Fig. 13. Photograph of Torn Plate with 6mm Beam Stiffener.

4. DISCUSSION

The effect of a single stiffener across a circular plate has been presented. The results indicate that the deflection of the plate is reduced by between 22% and 34% for the beams of thickness 3mm to 6mm respectively. However, the effect of the 5mm and 6mm beams appear to be similar, (Table 6, Figs.9 and 10). This implies that a beam with thickness more than 5mm is redundant for Mode I failure. It has also been shown that for the 3mm and 4mm beam stiffeners, these beams tear at impulses lower than that required to tear the plate; whereas for the 5mm and 6mm beams only the plate was observed to tear. The impulse required to tear the plate is identical for both the 4mm and 5mm beam stiffeners. Again this implies that a beam with thickness more than 5mm is redundant for Mode II failure. Hence for the given material properties and for plate/beam dimensions of 100mm diameter, 1,6mm thick/8mm wide, a beam thickness of 5mm is shown to be the optimum stiffener.

5. REFERENCES

1. JONES N, URAN T, TEKIN SA, "The Dynamic Plastic Behaviour of Fully Clamped Rectangular Plates". Int. J. Solids Struct. Vol.6, pp.1499 - 1512, 1970.
2. JONES N, GRIFFIN RN, AND VAN DUZER RE, "An Experimental Study into the Dynamic Plastic Behaviour of Wide Beams and Plates", Int. J. Mech. Sci., Vol. 13, 721 - 735, 1971.
3. JONES N, BAEDER, RA, "An experimental study of the dynamic plastic behaviour of rectangular plates". Symp. Plastic Analysis of Structures. Published by Ministry of Education, Polytechnic Institute of Jassy, Civil Engineering Faculty, Rumania, Vol.1, pp.476 - 497, 1972.
4. NURICK GN, PEARCE HT, MARTIN JB, "The Deformation of Thin Plates Subjected to Impulsive Loading", In "Inelastic behaviour of plates and shells" (Ed. L Bevilacqua), Springer Verlag, New York, pp.597 - 616, 1986.
5. NURICK GN, MARTIN JB, "Deformation of thin plates subjected to impulsive loading - A review". Part I: Theoretical considerations, Int.J.Impact Engng. Vol.8, No.2, pp.159 - 169, 1989.
6. DUFFEY TA, "The Large Deflection Dynamic Response of Clamped Circular Plates Subjected to Explosive Loading", Sandia Lab. Res. Report No. SC-RR-67-532, 1967.
7. SHEN WQ, JONES N, "A Failure Criterion for Beams Under Impulsive Loading", Int. J.Impact Eng.,Vol 12,pp.101 - 121, 1992.
8. SHEN WQ, JONES N, "Dynamic response and failure of fully clamped circular plates under impulsive loading", Int. J. Impact Engng. Vol.13,No.2, pp.259 - 278, 1993.
9. TEELING-SMITH RG, NURICK GN, "The deformation and tearing of thin circular plates subjected to impulsive loads", Int. J. Impact Engng. Vol.11, No.1, pp.77 - 91, 1991.

10. OLSON MD, NURICK GN, FAGNAN JR, "Deformation and rupture of blast loaded square plates" - Predictions and experiments, Int. J. Impact Engng. Vol.13, No.2, pp.279 - 291, 1993.
11. NURICK GN, SHAVE GC, "The deformation and tearing of thin squareplates subjected to impulsive loads" - An experimental study, Int. J. Impact Engng. Vol 18, No.1, pp.99 - 116,1996.
12. NURICK GN, OLSON MD, FAGNAN JR , LEVIN A, "Deformation and tearing of blast-loaded stiffened plates", Int. J. Impact Engng, Vol.16, No.2, pp.273 - 291, 1995.
13. NURICK GN,CONOLLY AG, "Response of clamped single and double stiffened rectangular plates subjected to blast loads", Structures under Shock and Impact III (Ed.PS Bulson) Computational Mechanics Publications, pp.207 - 220, 1994.
14. NURICK, GN, JONES N, VON ALTEN - RUESS GV, "Large Inelastic Deformation of T-Beams Subjected to Impulsive Loads", Structures under Shock and Impact III,(Ed PS Bulson) Computational Mechanics Publications, pp.191 - 206, 1994.
15. NURICK, GN, JONES N, "Prediction of Large Inelastic Deformations of T-Beams Subjected to Uniform Impulsive Loads." AD-Vol 48, High Strain Rate Effects on Polymer, Metal and Ceramic Matrix Composites and Other Advanced Materials, ASME 1995.
16. JONES N., Structural Impact, Cambridge University Press, Cambridge, U.K., 1989.